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1

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BREAKDOWN PROCESSES IN LARGE-AREA COLD-CATHODE VACUUM TRIODES

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ABSTRACT

Preionization of large-aperture high-pressure discharge-pumped gas lasers requires uniform 250-500 keV 10-100 mA cm^{-2} electron beams of typically 1-10 x 10^3 cm^2 in area. Impedance collapse due to cathode plasma expansion renders diode electron guns inefficient in this application. Introduction of a control grid limits gun current to low, controllable values until plasma closure of the cathode-grid gap occurs. However, field enhancement at the grid can cause cathode-grid or grid-anode arcs resulting in current runaway. An experimental study of impedance collapse was conducted by measuring element I-V characteristics in a 20 x 200 cm cold-cathode triode electron gun. Impedance collapse of the gun was dominated by two processes: (1) plasma closure of the cathode-grid gap and (2) grid-anode arcs. Plasma closure rate was ~2 x 10^6 cm sec^{-1} independent of configuration or interelectrode potential. Arc thresholds were found to depend (after conditioning) exclusively on local electric field strength at the grid which is, in turn, a function of grid bias and, more importantly, grid geometry. Streamers and arcs were occassionally observed in the cathode-grid region, phenomenon deserving of further investigation.

INTRODUCTION

Efficient, large aperture electron guns have become very important in development of high-power discharge-pumped gas lasers as inertial fusion drivers and for other research.[1] Uniform excitation of large aperture ($\gtrsim$10 cm^2) high pressure ($\gtrsim$100 torr) laser discharges requires prior generation of free electrons throughout the discharge volume. X-ray, UV, and hybrid preionization techniques are limited in the volumes through which they can produce the required free electron densities (~10^{13} cm^{-3}). For large volume lasers, direct injection of an electron beam has proven to be the most versatile, efficient, and effective means of controlling discharge characteristics.[2]

Typical beam currents required are 10-100 mA cm^{-2} of 250-500 keV electrons. Total beam area may be up to 10^5 cm^2 but that is typically comprised of several beams of area 1-10 x 10^3 cm^2 each. Current risetimes of $\lesssim$ 1 μsec and pulse durations of 2-10 μsec are typically required.

Until recently, cold-cathode space-charge-limited diode electron guns have generally been employed. Beam current for such a diode is given by the Child-Langmuir Law:

$$I_K = \frac{A}{9\pi} \left[\frac{2e}{m_e}\right]^{\frac{1}{2}} \left[d_{K-A} - v_c t\right]^{-2} V_{K-A}^{\frac{3}{2}} \qquad (1)$$

where A is the gun area, d_{K-A} is the cathode-anode physical separation, v_c is the plasma closure velocity, and V_{K-A} is the cathode-anode potential difference. If $v_c T$ is significant compared to d_{K-A}, a diode is fundamentally incapable of delivering a constant current pulse at a fixed voltage. All design trade-offs lead to inefficient use of the energy stored in the gun pulser. Efficiency can be improved by using a triode configuration in which the control grid is biased by connecting it to the gun anode through a fixed resistor, R_G. Gun cathode current is then specified by the transcendental equation

$$I_K = \frac{A}{9\pi}\left[\frac{2e}{m_e}\right]^{\frac{1}{2}}\left[d_{K-G} - v_c t\right]^{-2}\left[V_{K-A} - (1-t_G)I_K R_G\right]^{\frac{3}{2}} \quad (2)$$

$(1-t_G)I_K R_G$ represents the grid-anode potential difference if t_G is the grid transmission.

The triode gun offers two advantages over the diode: (1) current is limited to a stable range until cathode-grid closure is nearly complete (at which point the device becomes a diode again), and (2) current may be adjusted by varying the bias resistor. These characteristics lead to improved efficiency of the gun circuit. However, introduction of the grid complicates the structure and introduces new fault modes. This paper reports results of an experimental study into arc formation and plasma closure phenomena in a large area cold cathode triode electron gun.

EXPERIMENTAL CONFIGURATION

To determine breakdown limits to gun operating parameters, I-V characteristics of a 20 x 200 cm planar cold cathode gun were measured under conditions of maximum electrical stress. For this study, the normal anode hibachi structure and Kapton/Al pressure window were replaced with a flat stainless steel plate. The cathode was a segmented 200 cm long ribbon of 12 μm Ta foil. Several grid materials were used. The grid plane was fixed 23 cm from the cathode and 6.4 cm from the anode.

In the configuration employed for this experiment, the anode is grounded and the grid is biased from it through a $CuSO_4:H_2O$ resistor, R_G. The cathode is driven from a 7 stage Marx generator having an effective capacitance of 0.142 μF, a measured L of 32 μH, and a maximum open-circuit discharge voltage of 600 kV.

Four different control grids were interchangeably employed. Numbers 1 and 2 consisted of .48 cm diam stainless steel rods spaced 2.54 or 1.27 cm apart, respectively, oriented transverse to the cathode. Grids numbered 3 and 4 employed a two-dimensional mesh, elements of which were rectangular wires .13 cm wide by .09 cm thick on 1.27 (grid 3) or 0.64 cm (grid 4) centers.

RESULTS AND INTERPRETATION

A. GENERAL

Breakdown of the triode was defined by a rise in cathode current substantially above that calculated with Eq. (2). Initial studies indicated two basic types of breakdowns occurred: plasma closure of the cathode-grid region and arcs between grid and anode. These are discussed individually in parts B and C of this section.

Parametric studies indicated neither breakdown mode was significantly affected by changes in cathode blade condition, anode material or surface finish, or vacuum in the gun (normally 1.2×10^{-6} torr pumped by an untrapped oil diffusion pump, but allowed to rise to 1.0×10^{-4} torr to ascertain effect). Electropolishing the grids to eliminate any sharp edges or points led to little, if any, significant change in breakdown characteristics. After exposure of the gun to air, a few (3-5) conditioning shots were found helpful in achieving reproducibility of subsequent data.

B. CATHODE-GRID PLASMA CLOSURE

Explosion of cathode micropoints heated by field emission current is well known to create plasmas which expand across and eventually short the interelement region of a cold cathode diode.[3] This phenomenon is also observed in the cathode-grid region of a triode. The cathode current in Fig. 1a shows an example of the normal early peaking and subsequent decay of the cathode current followed by a rapid rise. After the initial rise to peak, I_K is well predicted by solution of Eq. (2) with $v_c = 2.0 \times 10^6$ cm sec^{-1}. Figure 1b shows that the rise in I_K occurs when V_{K-G} reaches zero, indicating complete closure. Fits of Eq. (2) to I-V curves from other shots yielded closure velocities of $1.5 - 2.7 \times 10^6$ cm sec^{-1}. This behavior is consistent with that routinely observed in diode guns at comparable cathode current.

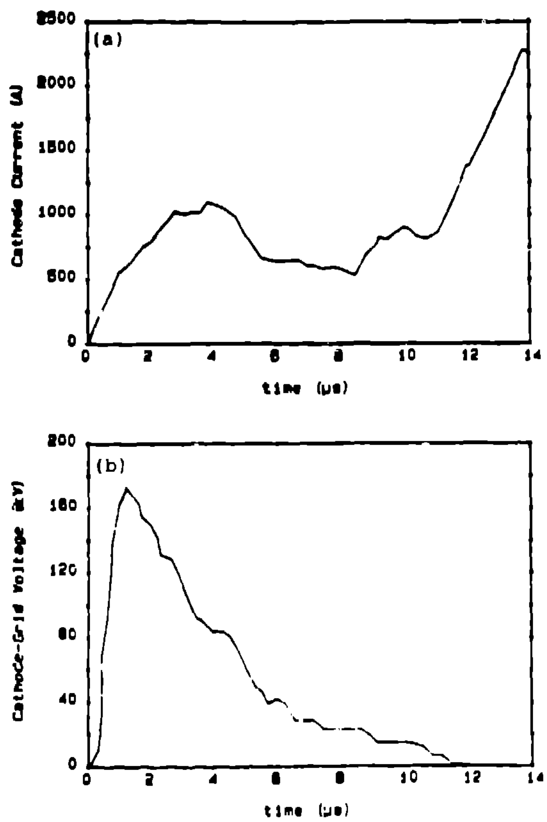

FIGURE 1. (a) I_K and (b) V_{K-G} of triode during plasma closure of K-G gap. V_{K-A} = 350 kV, R_G = 1290 Ω.

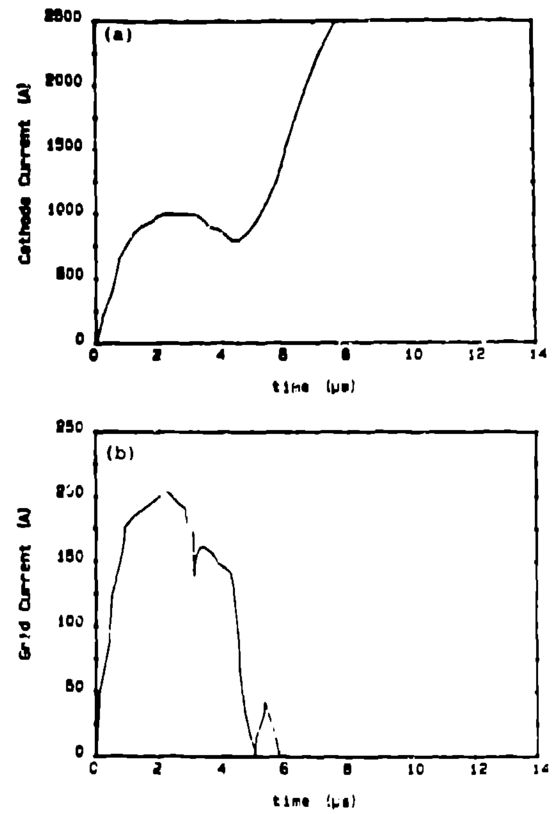

FIGURE 2. (a) I_K and (b) I_{R_G} of triode (using grid 1) with G-A arc at 5 μsec. V_{K-A} = 350 kV. R_G = 1290 Ω. Such arcs may occur at 2-10 μsec. Risetime is limited by power supply inductance.

C. GRID-ANODE ARCS

Breakdown of the type illustrated in Fig. 2 occurred at grid-anode potentials which depended on which grid was in use. Results are summarized in Table I.

TABLE I

Breakdown Potential for Triode E-Gun

Grid	Type	t_G	$E^{Breakdown}_{G-A}$ (kV cm^{-1})
1	Rod	.81	32
2	Rod	.62	45
3	Mesh	.81	24
4	Mesh	.62	32

Calculation of the electric field in the triode proceeds in two steps. First, the field of a triode in which cathode current is space-charge limited is calculated in all interelectrode regions.[4] $|\vec{E}|$ is clearly maximum near the grid surface. Using equipotential lines from the preceeding calculation as boundary conditions, Laplace's equation may be solved (the space charge can be ignored) to yield a good approximation to the field immediately surrounding the grid. This two-step approach provides high resolution in the region of interest without consuming inordinate calculation time. Results are summarized in Table II.

TABLE II

Breakdown Threshold at Triode Grid

Grid	E^{avg}_{G-A} (kV cm^{-1})	E^{max}_{G-A} (kV cm^{-1})	$\frac{E^{max}}{E^{avg}}$
1	32	64	2.0
2	45	63	1.4
3	24	74	3.1
4	32	71	2.2

Regardless of grid type, breakdown occurs when E^{max} reaches ~70 kV cm^{-1}. This is consistent with Kilpatrick's breakdown measurements for a DC field[5], resulting in an extremely simple criterion for determining maximum voltages that a given triode of this type can withstand.

A design trade-off is implied, however. Reduction of field enhancement (E^{max}/E^{avg}) at the grid to permit higher beam voltages requires a grid with lower transmission, resulting in lower beam current.

D. CATHODE-GRID STREAMERS AND ARCS

Several shots employing the mesh grids produced immediate (commencing at <1 μsec) arcs between cathode and grid. No beam current is ever generated. Cause and a predictive model for this infrequent and erratic behavior are still being sought.

Cathode and grid voltage and current waveforms for many shots showed evidence of streamer formation between cathode and grid for the first 6 μsec of the shot. These streamers never developed into full arcs and had no reproducible correlation to later grid-anode breakdowns. This phenomenon also deserves further study as these streamers could be precursors to catastrophic breakdown under other operating parameters.

SUMMARY

Two different, predictable processes limit the operation of large-aperature cold-cathode vacuum triodes. First, plasma closure of the cathode-grid gap at ~2 x 10^6 cm sec^{-1} limits the period during which grid control can be maintained. Second, DC breakdown occurs between grid and anode when maximum local electric field near the grid surface reaches ~70 kv cm^{-1}. Other cathode-grid breakdown processes are occasionally observed but have not yet been explained or modelled.

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